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THERMAL REGIME OF THE RESERVOIR OF THE VILYUYSKAYA HYDROELECTRIC POWER STATION AND THE PERMANENTLY FROZEN GROUND OF ITS BED

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The construction of the first major hydroelectric complex, the Vilyuyskaya Power Station, in a permafrost region, raised problems for planners and engineers concerning the specific conditions of erection and operation of the structures. This report discusses their problems and findings.

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THERMAL REGIME OF THE RESERVOIR OF THE VILYUYSKAYA HYDROELECTRIC POWER STATION AND THE PERMANENTLY FROZEN GROUND OF ITS BED

Moscow KOLYMA in Russian No 8, 1972, pp 30-33

[Article by R. M. Kamenskiy and I. P. Konstantinov, Permafrost Institute Siberian Department USSR Academy of Sciences]

[Text] The construction of the first major hydroelectric complex, the Vilyuyskaya Hydroelectric Power Station, in the regions of occurrence of permafrost and a severe climate, raised before planners and engineers problems caused by the specific conditions of erection and operation of the structures in the hydroelectric complex.

The most important structure of the hydroelectric station is the dam, which under the conditions of the Far North is preferably made from local construction materials. The antifiltration and static stability of such a dam is determined to a considerable degree by the thermal regime of the structure, which is formed under the joint influence of different thermophysical processes. Naturally, one of the principal factors determining the thermal state of the body and foundation of the dam is the reservoir, whose thermal regime and whose dynamics are extremely uncertain in this case and require special study.

On the other hand, the formation of a large artificial water body (length 400 km, area 2,170 km^2, volume 36 km^3, depth up to 70-80 m), the bed and shores of which consist of permanently frozen ground, in individual cases very icy, with inclusions of an ice complex, raises anew the problem of studying the reformation of the shores and possible infiltration as the bed bottom material thaws.

Taking into account the importance of study of the thermal regime of the reservoir and the permanently frozen ground of its bottom for validating thermotechnical methods for designing hydroengineering structures in regions with permanently frozen ground, the Vilyuyskaya Scientific Research Permafrost Station of the Permafrost Institute Siberian Department USSR Academy of Sciences since 1967 (from the time of onset of filling of the

reservoir of the Vilyuyskaya Hydroelectric Power Station) is systematically carrying out field observations of the distribution of water temperature in the sector of the reservoir near the dam (approximately 800 m above the upper line of the dam) and of the dynamics of the temperature field of the bottom material in its bed. Since 1970 specialists have also been making seasonal observations of the formation of the thermal regime of the coastal (shallow-water) zone of the reservoir in its different parts with a detailed analysis of the diurnal variation of temperatures in dependence on depth, microclimate and other factors.

For comparison and use of the results of the field observations presented in the article we will give the principal climatic characteristics of the region.

The basin of the Vilyuy River belongs to the East Siberian Climatic Region. Table 1 gives the mean monthly and mean annual air temperatures for a six-year period of observations: on the basis of data for the meteorological station at Chernyshevskiy village.

The transition of the mean daily air temperature through 0° occurs in the neighborhood of Chernyshevskiy village in spring, during the first ten days of May, and in the autumn -- in the second ten days in September. The number of frost-free days does not exceed 70-74. The mean annual wind velocity is 3.6 m/sec.

The method for carrying out field observations of the thermal regime of the reservoir and the underlying frozen layers is as follows. The water temperature is measured using strings of thermistors along three verticals on the line perpendicular to the axis of the reservoir (Fig. 1). The intervals of depth measurements were from 1 to 5 m. For observations of the dynamics of the temperature field of permanently frozen ground in the reservoir bed specialists set up a special geothermal line of three boreholes, each with a depth of 50 m. The boreholes were cased with watertight steel sleeves into which the strings of thermistors were embedded. The sleeves were filled with niger oil and in the upper part, to a depth as great as 3 m, were sealed with bitumen. Temperature measurements are made remotely from an observation panel mounted at a site away from the reservoir. The underwater lead from the boreholes to the panel was made with a special control cable of the KVRB 19 x 0.5 type. The periodicity of all measurements was one month. Measurement accuracy was 0.1°.

Although the filling of the reservoir began in 1967, the most stable and near-planned water levels have been observed only since 1969. Therefore, the total observation time covers a small period and the conclusions which were drawn on the basis of these observations are of a preliminary nature.

At the beginning of the spring period, when the mean daily air temperatures pass through 0°, the thermal regime of the reservoir is characterized by a virtually linear distribution of temperatures with depth with an

insignificant gradient. The water temperatures were minimum (Fig. 2.1).

As the snow melts, the melt water arrives from the slopes, the ice cover is destroyed and the surface layers of water are heated by means of penetrating solar radiation, the thermal regime of the reservoir forming by the onset of the spring period is impaired. A distinguishing characteristic of the regime becomes a considerable areal nonuniformity. For example, in the headwater embayments in the shallow-water sectors as a result of their early opening up (freeing from ice) there is a direct stratification with a rather high temperature of the surface layers during the daytime (up to 12-14°), whereas in sectors of the reservoir where the ice cover persists there is a reverse stratification with temperatures of 2-4° (Table 2).

Table 1

Месяцы A												B
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
−31,6	−30,1	−17,0	−7,0	+2,2	+12,2	+16,8	+13,5	+3,8	−6,7	−23,2	−30,5	−8,3

A) months; B) mean annual temperature, degrees

Table 2

Глубина, м A	Май B					Июнь C			
	18	20	23	24	28	4	8	12	18
0,1	0,16	0,26	0,30	0,23	0,52	2,81	2,85	3,69	9,44
2,0	1,83	2,0	2,31	2,35	2,40	2,68	2,80	3,71	4,65
5,0	1,82	2,0	2,29	2,30	2,57	2,37	2,78	3,38	3,90
D Средняя температура по вертикали, град	1,27	1,42	1,63	1,63	1,83	2,62	2,81	3,59	6,0

E *Примечание.* С 4 июня ледовый покров разрушился.

A) Depth; B) May; C) June; D) Mean temperature along vertical, degrees; E) Note. Beginning on 4 June the ice cover was destroyed

The melt water flowing from the slopes with a temperature close to 0° favors the cooling of the water and to some degree governs the duration of the period of spring homothermy. As a result of this, after total clearing of the reservoir from its ice cover (10-15 June) the temperature of the bottom layers of water is reduced by 0.2-0.5° with considerable heating and great gradients of temperature in the surface layers. Beginning with the second half of June there is intensive summer heating of the reservoir and this period is characterized by stable stratification with considerable water temperature gradients with depth (Fig. 2, II).

The maximum difference between the water temperatures at the surface and at the bottom is observed during the second ten-day period in July when the air temperature attains its maximum. In the sector of the reservoir near

the dam ("canyon sector") this difference attains 10-15°.

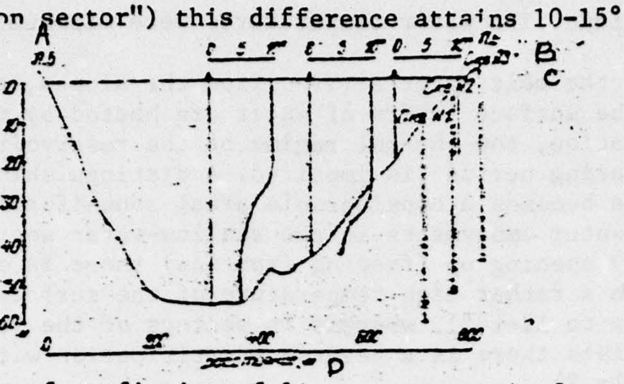

Fig. 1. Diagram of outfitting of line on reservoir for temperature observations. A) Left side; B) Right side; C) Borehole; D) Distance, m

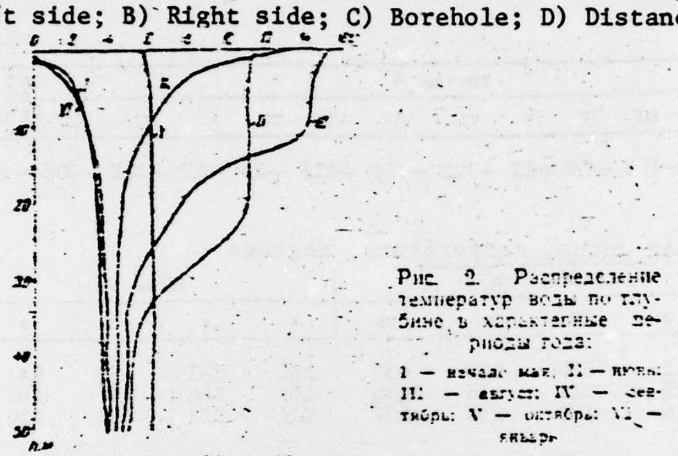

Fig. 2. Water temperature distribution with depth during characteristic periods of year: I) beginning of May; II) June 11; III) August; IV) September; V) October; VI) January

The heating of the reservoir occurs nonuniformly in its different parts. In mid-June 1971 a rapid temperature survey was made along the length of the reservoir in a sector of 60 km. The water temperature was measured in the entire depth using a GM9 bathythermograph. The results of the measurements were processed in the form of mean temperatures with depth. Their analysis revealed that the lowest water temperature is observed in the canyon and deep-water sectors of the reservoir. In broadenings the mean water temperature is greater by 1.5-2° and lesser temperature gradients with depth as a result of wind mixing.

The maximum heating of the water mass is observed in late August - early September. During this period in the sector of the reservoir in the vicinity of the dam there are mean temperatures with depth (9-10°). The nature of the temperature distribution with depth is shown in Fig 2, IV.

The cooling of the surface layers of water begins in late August in connection with a decrease in air temperature, a decrease in the receipts of solar radiation and an intensification of wind mixing. In the shallow-water sectors of the reservoir homothermy is established relatively rapidly with water temperatures of 12-14° and a further decrease in temperature occurs uniformly through the entire layer. In the deep-water sectors homothermy is established in the second-third ten-day period of October with temperatures 4-6° (Fig. 2, V). In the period of autumn cooling of the reservoir the principal role in the heat exchange of different water layers in its canyon sectors is played by free convection, whereas in the broadenings the main role is played by wind mixing. Nevertheless, during this period there is no significant difference in the dynamics of the thermal regime of the reservoir in its different sectors.

Ice formation on the reservoir ends during the first ten days in November with water temperatures of 3-4°, averaged for the vertical cross section. In the shore zone and in shallow-water sectors an ice cover is formed beginning with the second half of October with water temperatures averaging about 2° in the vertical cross section. During the first 30-40 days after the ice sets in there is some increase in water temperature (by 0.2-0.4°) due to heat exchange with the bottom material of the floor and then during the entire winter there is a gradual decrease in water temperature in the entire depth. An increase in thickness of the ice cover occurs to the end of March and the maximum ice thickness in the reservoir is 10-15% greater than on the Vilyuy.

A general analysis of data from field observations of the thermal regime of the reservoir from the point of view of the thermal effect on the structure of the hydroelectric power station and on the shore makes it possible to note the following.

In the coastal zone of the reservoir and in the shallow-water sectors the average water temperature in the vertical cross section during the summer is higher and during the winter it is lower than in the deep-water canyon sectors. In general, for the year the mean water temperature for the vertical cross section increases with a decrease in depth. A similar picture is also traced with respect to the mean annual temperature of the bottom layers of water. For example, in the shore zone of the reservoir with depths of 5-15 m this temperature is 5.1°, whereas in the channel part with depths of 50-60 m it is 4.2°. It can be assumed that as time elapses this difference in temperatures will increase as the permanently frozen material of the bed in the coastal zone is heated and thaws. It should be noted in this connection that in the channel part of the reservoir during the engineering field work a talik of considerable thickness was also discovered (it is postulated that it is a "through" talik) with a mean annual temperature in the upper horizons of 4°.

It is also important to note this fact. The mean water temperature in the transverse cross section and in depth (annual temperature) in the part of the reservoir near the dam at the present time is 4.6°. This temperature is close to the mean water temperature computed for the reservoir in the course of planning (5°). Nevertheless, there is basis for assuming that with a great period of operation of the hydroelectric complex the mean annual water temperature will be somewhat greater than was predicted.

For hydroengineering computations of the thermal regime of the foundation and body of the dam during the first years of operation the mean annual water temperatures in the reservoir can be accepted as adequately sound.

Simultaneously with observations of the thermal regime of the reservoir at these same times and in the same cross section observations were made of the dynamics of the temperature field of rocks in the bed of the coastal zone (Figures 1 and 3).

The lithological cross section of the shore slope is as follows: deluvial clayey loams with gruss and rubble of bedrock to a depth of 0.5-0.7 m (to a depth of 10-15 m fractured) with the following thermophysical properties: $\gamma = 1,970$ kg/m^3; $\lambda_T = \lambda_M = 1.90$ Cal/m·hour·degree; $C_T = C_M = 0.167$ Cal kg; $w \approx 0.3\%$.

The temperature observations were initiated in borehole No 1 beginning on 5 May 1969 immediately after outfitting the boreholes with thermometric apparatus.

Since borehole No 1 was drilled after digging of the reservoir in the shore zone, twice inundated (in 1968 and 1969), the natural temperature regime of the rocks was somewhat impaired by the time of onset of the observations. In boreholes Nos 2 and 3, after outfitting the borehole and "standing" the instruments registered the natural temperature regime which was observed on the slope during engineering field work.

Beginning with the second half of May 1969, borehole No 1 fell into a zone of constant inundation. The depth of the water layer over the borehole during the observation period varied from 2.5 to 12 m in dependence on fluctuations of the water level in the reservoir. Borehole No 2 entered into the zone of inundation during the first days of June; it varied from 2.5 to 12 m in dependence on fluctuations during the observation period from 0.8 to 6.5 m. Borehole No 3 was situated outside the inundation zone, although the water line beginning with the second half of May 1971 approached the very edge of the borehole.

For analysis of data on the dynamics of the plane temperature field of the perennially frozen rocks in the reservoir floor Figure 3 shows the temperature distribution with depth in three boreholes at similar moments in time during the period from December 1969 through December 1971. In 2.5 years the frozen rocks thawed to a depth of 7.75 m (in the first borehole),

whereas the thermal influence of the reservoir was propagated to a depth of 22 m. In boreholes Nos 2 and 3 there is an impairment of the natural temperature field to depths of 24 and 30 m respectively; the greatest depth was noted in borehole No 3, which is situated outside the inundation zone. This can be attributed only to the warming influence of the reservoir.

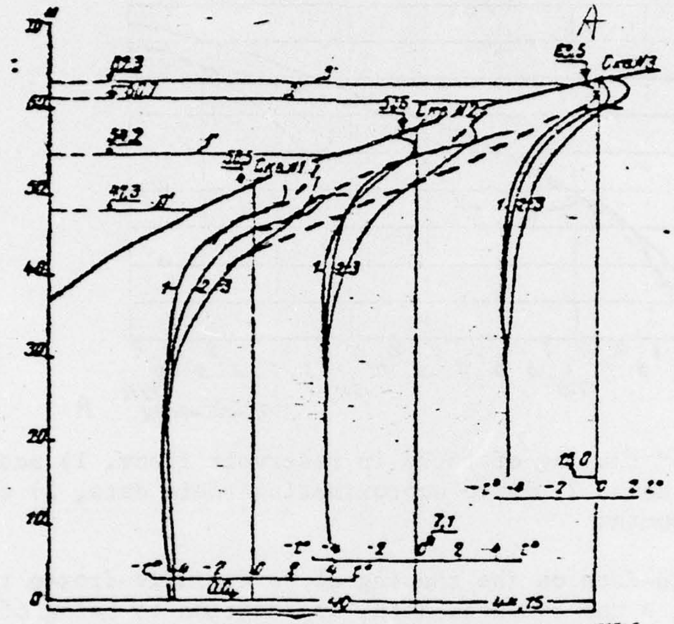

Fig. 3. Dynamics of temperature field of perennially frozen rocks in the bed and shore zone of the reservoir: 1) temperature distribution with depth at initial moment of time (December 1969); 2) October 1970; 3) December 1971; 1', 2', 3') water levels in reservoir at corresponding observation moments; 0') water level on 5 May 1969. A) Borehole

The dynamics of thawing of the rocks on the basis of data from measurements in borehole No 1 is shown in Fig. 4. In accordance with the seasonal fluctuations in the temperature of the bottom layers of water during the course of the year there is also a change in the intensity of thawing and although the general direction of the process is an increase in the thickness of the thawed layer, during the winter there is a decrease in the depth of thawing due to freezing from below when the bottom water layers have a temperature of about 1.0-1.5°. Curve 2 in Fig. 4 approximates (averages) the general variation of thawing in the reservoir bed and it is close to the theoretical curve (3), which is computed on the basis of the well-known formula derived by V. T. Balobayev [1] on the basis of field data on the mean annual temperature of the bottom layers of water in the coastal zone (+5°), the

actual temperature of the perennially frozen ground at the depth of the thermal influence of the reservoir (minus 4.3°) and the thermophysical characteristics of the diabases making up the reservoir floor. The computations do not take into account the thin layer of deluvial deposits; this evidently can explain the fact that the actual depth of thawing is somewhat less than the computed value.

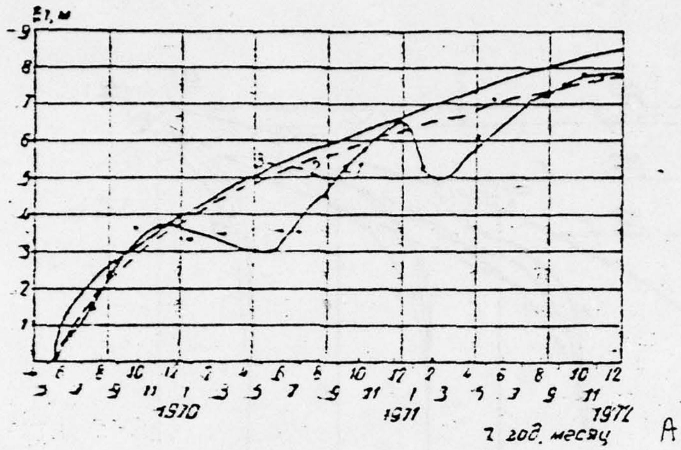

Fig. 4. Dynamics of thawing of rocks in reservoir floor. 1) according to field measurement data, 2) curve approximating field data, 3) computed curve. A) years, months

Comparison of field data on the thawing of perennially frozen rocks in the reservoir floor with the computed data, in addition to being of purely theoretical interest, also is of practical importance because it makes it possible to conclude that the analytical formulas derived for unidimensional conditions can be used in definite limits for evaluating the thermal influence of the reservoir on the perennially frozen ground of the bed even in the relatively near neighborhood of the shoreline.

For a qualitative and quantitative evaluation of the thermal influence of the reservoir on the perennially frozen ground of the shore zone it is necessary to obtain data on the dynamics of the temperature of rocks at different distances from the shore.

In general, the results of field observations make it possible to conclude that there is a weak intensity of the processes of heat exchange between the reservoir and the underlying perennially frozen ground (even rocky material, in the case of a minimum ice content), which is governed to a considerable degree by the thermal regime of the reservoir and the low temperature of the rocks.

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